NAVAL HEALTH RESEARCH CENTER

CIRCADIAN RHYTHMS:

IMPORTANCE FOR MODELS OF COGNITIVE PERFORMANCE

T. L. Kelly

Report No. 96-1

NAVAL HEALTH RESEARCH CENTER
P. O. BOX 85122
SAN DIEGO, CALIFORNIA 92186 – 5122

NAVAL MEDICAL RESEARCH AND DEVELOPMENT COMMAND
BETHESDA, MARYLAND

CIRCADIAN RHYTHMS: IMPORTANCE FOR MODELS OF COGNITIVE PERFORMANCE

Tamsin Lisa Kelly, J.D., M.D.

Naval Health Research Center
P.O. Box 85122
San Diego, California 92186-5122

Report No. 96-1, supported by the Naval Medical Research and Development Command, Department of the Navy, under Work Unit No. 61153N MR04101.003.6410. The views expressed in this document are those of the author and do not reflect the official policy or position of the Department of the Navy, the Department of Defense, or the U.S. Government. Approved for public release, distribution is unlimited.

EXECUTIVE SUMMARY

Problem

Accurate models of human cognitive performance would be valuable operational aids. Circadian rhythms may be important variables that could improve the accuracy of such models.

Objective

The objective of this report is to demonstrate the importance of circadian rhythms for accurate prediction of cognitive performance.

Approach

The approach taken was to review the literature on the effect of circadian rhythms on human cognitive performance.

Results

The literature shows that the circadian rhythms of cognitive performance are of sufficient amplitude to have practical significance for modeling. When expressed as a percentage of average performance, circadian variation averages about 20% in laboratory studies and 40% in field studies. Decrements due to circadian rhythms can be greater than those due to sleep deprivation. Sleep deprivation amplifies performance rhythms, causing greater decrements at the time of the circadian nadir (early morning) than during the daytime. Thus, decrements in the early morning can be quite dramatic in sleep-deprived subjects. Although different types of performance differ in the exact phase of their circadian rhythms, most cognitive performance rhythms are fairly well aligned with the circadian rhythm of body temperature. Tasks involving a high short-term memory load may be an exception, sometimes showing rhythms almost 180° out of phase with temperature. After travel across multiple time zones, individuals initially show rhythms in phase with the home-base clock. Rhythms adjust to the new time zone at a rate of about 90 min per day after westward travel and 60 min per day after eastward travel. Several factors can speed or slow adjustment, particularly the timing and duration of bright light exposure.

Conclusion

Incorporation of information about circadian rhythms is crucial for accurate prediction of cognitive performance. If circadian rhythms are not accounted for in models of human performance, predictions could be inaccurate. This is particularly true for models of performance during SUSOPS or other situations where sleep is markedly decreased. Any model that includes circadian rhythms must make allowance for readjustments after travel across multiple time zones. Otherwise, inclusion of circadian factors could decrease rather than increase accuracy of a model.

Introduction

The objective of this paper is to provide information about circadian rhythms and their relevance to the development of models of human cognitive performance. Circadian rhythms are well-established characteristics of human performance. However, to date, models of human performance generally have not taken them into account. The general effects of circadian rhythms will be reviewed, followed by a discussion of the interaction of sustained operations (SUSOPS) and jet lag with these rhythms. Individual differences in circadian rhythms will be addressed, and some published circadian rhythm models will be discussed. While physiological aspects of performance also show circadian rhythms, fluctuations in cognitive performance are more pronounced and will be the focus of this report.

Circadian Rhythms

Circadian (about 24 hr) rhythms are daily fluctuations in physiological and behavioral functions generated by single or multiple internal pacemakers (Kelly, Smith, & Naitoh, 1989). Under normal circumstances, these rhythms cycle once per 24 hr. However, subjects isolated from sunlight exposure and from synchronizing time cues show unique endogenous cycle lengths that are generally longer than 24 hr. Circadian fluctuations are present all the way from the biochemical and cellular levels of physiology (Nicolau & Haus, 1989; Rivera-Coll, Fuentes-Arderiu, & Diez-Noguera, 1993; Sletvold, Smaaland, & Laerum, 1991), through higher-level physiological measures (Cugini, et al., 1993), to all types of physical (Winget, DeRoshia, & Holley, 1985) and cognitive (Blake, 1967; Brown & Graeber, 1982; Gillooly, Smolensky, Albright, Hsi, & Thorne 1990) performance. Figure 1 shows the typical circadian rhythm of body temperature, the most commonly used "gold standard" marker of circadian rhythms. Most people following a normal schedule who have not recently crossed multiple time zones will show a temperature nadir (low point) around 0400 - 0600, with an acrophase (peak) in the afternoon. The same pattern of high temperatures during the day and lower temperatures at night is seen when exogenous effects on temperature variation are controlled by keeping subjects awake, at bed rest, with small equivalent hourly feedings. Thus, circadian rhythms are driven by an internal pacemaker and are not secondary to environmental influences.

Circadian Rhythms in Cognitive Performance

At least for well-learned relatively simple tasks not requiring extensive retention of information in short-term memory, the peaks and troughs of performance appear to conform fairly closely to those of the circadian temperature rhythm (Folkard, 1981; Klein & Wegmann, 1979; Wilkinson, 1982). Relevant findings of some studies are summarized in Table 1. Note that in Table 1 the acrophase and nadir refer to best and worst performance, respectively. Thus, for positive measures, such as speed, the acrophase is the high point, but for negative measures, such as errors, the acrophase is the low point.

Circadian rhythm-related variation has been well documented for some types of performance. Gillooly et al. (1990) collected data on five tasks from the Walter Reed performance assessment battery (PAB) repeated at hourly intervals. Testing sessions commenced at either 2000 or 0800 and lasted 13 hr, so data were available from all hours of the day without requiring subjects to remain awake for 24 hr. Individual and group cosinor analyses documented circadian rhythms on most performance measures. The extent of this variation, expressed as a percentage of the mean performance, averaged 21% for throughput measures (range = 8% to 36%). Throughput is a combined accuracy-speed measure, number of correct responses per unit of time. The Serial Add/Subtract task (shown in Figure 2) and Logical Reasoning task showed the largest circadian variation. Arguably, these two tasks were the most similar to actual operational tasks in their degree of difficulty. Averaged over subjects, maximal performance speed and highest throughput for most tasks occurred around 1800 to 1900. Time of maximum accuracy was more variable. Performance tended to be most variable around 0500-0700 (subjects would have been awake all night at that point, so this could be a circadian effect, a fatigue effect, or both).

Blake (1967) also reported time of day effects on performance of PAB type tasks. Subjects in that study were tested at different times of day (0800, 1030, 1300, 1530, and 2100) on different days, using a Latin square design to eliminate practice effects. Tasks (most lasting about 30 min) included Five-Choice Reaction Time, Vigilance (shown in Figure 3), Card Sorting, Letter Cancellation, Time Estimation, Digit Span, Simple Reaction Time, and Addition. Most tasks showed a tendency for performance improving through the day, except for a temporary drop after lunch

Table 1: Selected Circadian Rhythm Studies

Study	Measures	Amplitude % of Mean	Acrophase- -Best	Nadir --Worst (Lesser Low)
Blake, 1967	speed, accuracy	N/A	2100, (digit span, 1030)	N/A
Folkard et al., 1976 (memory search)	2-letter	N/A	1700-2100[1]	0300-0800[1]
	6-letter	N/A	2400-0300[1]	1200-1600[1]
Fröeberg et al., 1975	shooting	normal 20% sleep deprived 80%	1700	0500
Gillooly et al., 1990	speed, accuracy, throughput	21% (8%-36%)	1800-1900 (speed & throughput)	0430-0630[1]
Hildebrant et al., 1974	locomotive driver errors	100%[1]	1800-2400 (0700-1000)	1300 (0300)
Klein et al., 1976	lab - speed	12-25%	12-2100	0300-0600
	field - errors	60-100%	N/A	N/A
Mitler et al., 1988	fatigue accidents	190%[1]	1800[1]	0200 (1400)[1]
	meter errors	90%[1]	0800[1]	0200 (1400)[1]
Monk & Leng, 1986	letter search speed	N/A	1600	N/A
	logic speed	N/A	0700 - larks, 1300 - owls	N/A
Opstad, 1994	code test logical reasoning	normal - 10% sleep deprived - 80%	N/A	N/A
Rutenfranz & Colquhoun, 1979	asleep at wheel	140%[1]	0800 (1800)	2400 (1400)

[1]These numbers have been estimated from graphs in the paper.

(sometimes referred to as "the lesser circadian low" or "the postlunch dip"), and best performance at 2100, with changes in performance closely following changes in body temperature. Digit Span (shown in Figure 4) was unique in showing peak performance at 1030, with decreasing performance thereafter, and worst performance at 2100.

The amount of circadian variation in cognitive functions ("amplitude," or peak-to-trough difference) can be quite substantial and is affected by characteristics of both the task and the subject. Klein, Wegmann, Athanassenas, Hohlweck, and Kuklinski (1976) summarized the effects of several factors on circadian performance variation (see Figure 5). In general, the amount of variation across the circadian cycle is found to range between 12% and 25% (or $\pm$5% and $\pm$15%) of the mean performance level. In field studies, where time on shift, motivation level, and environmental conditions can play a larger role, higher amplitude fluctuations ($\pm$30% to $\pm$50% of the mean) are seen. Individuals with higher performance levels tend to show smaller circadian ranges of oscillation. The range as a percentage of the 24-hr mean in individuals with the worst mean performance is double that of those with the best. Practice or training increases the circadian mean and decreases the amplitude because it has the most effect on performance at the circadian nadir. Increasing motivation appears to have similar effects. Sleep deprivation drops the mean and increases the amplitude, having greatest effect at the circadian nadir. If an individual with average skills is sleep-deprived, he will perform at a level comparable to a less skilled individual who is well rested. Night-shift work and jet lag decrease both the mean and the amplitude, and have the greatest effects at the acrophase.

Some evidence suggests that tasks with high memory load may show rhythms in which the phase of maximal and minimal performance are out of the usual synchrony with body temperature.[2] Such a shift is apparent in the plot of Digit Span (Figure 4), a memory task. Since many real-world tasks will involve remembering various amounts and types of information for differing amounts of time, alterations related to memory requirements could greatly complicate modeling performance. The performance rhythm for high memory-load tasks has been reported to be almost 180° out of phase with temperature (Blake, 1967; Folkard, 1981; Folkard, Knauth, Monk, & Rutenfranz, 1976;

---

[2]Other data suggest performance involving high memory load may sometimes show a non-24-hr (21-hr) rhythm (Folkard, Wever, & Wildgruber, 1983). However, Folkard et al.'s study involved only 3 subjects and was performed in temporal isolation. So, the extent to which the findings would translate into real-world situations is questionable.

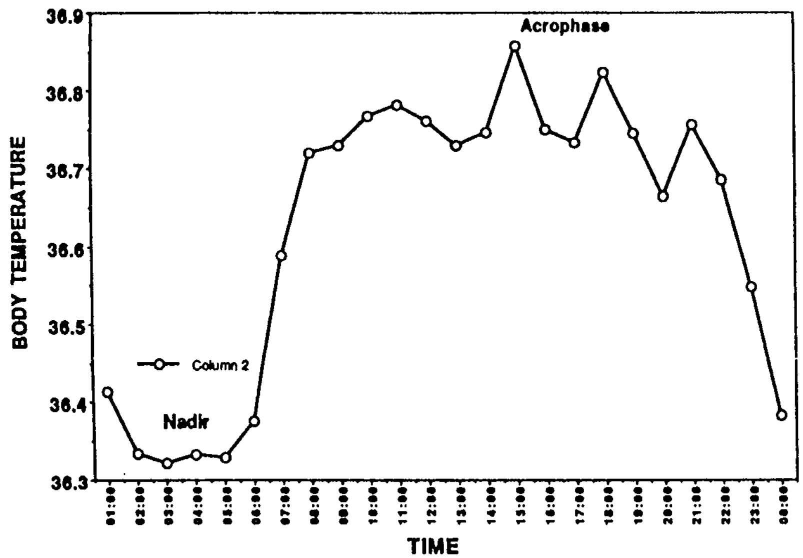


Figure 1. Circadian Rhythm of Body Temperature

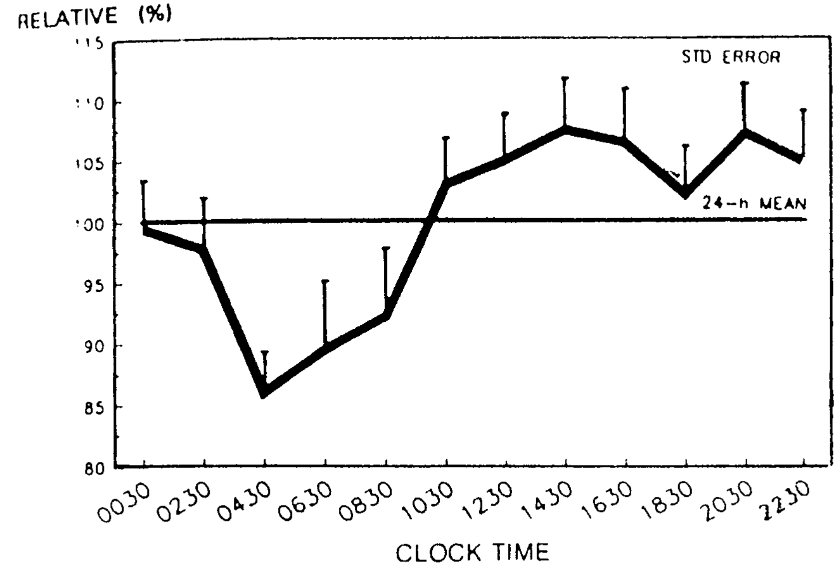


Figure 2. Serial Add/Subtract Performance. Reprinted with permission of the International Society of Chronobiology from "Circadian variation in human performance evaluated by the Walter Reed performance assessment battery," by Gillooly et al., CHRONOBIOLOGY INTERNATIONAL, Vol. No. 7, pp. 143-153. Copyright 1990.

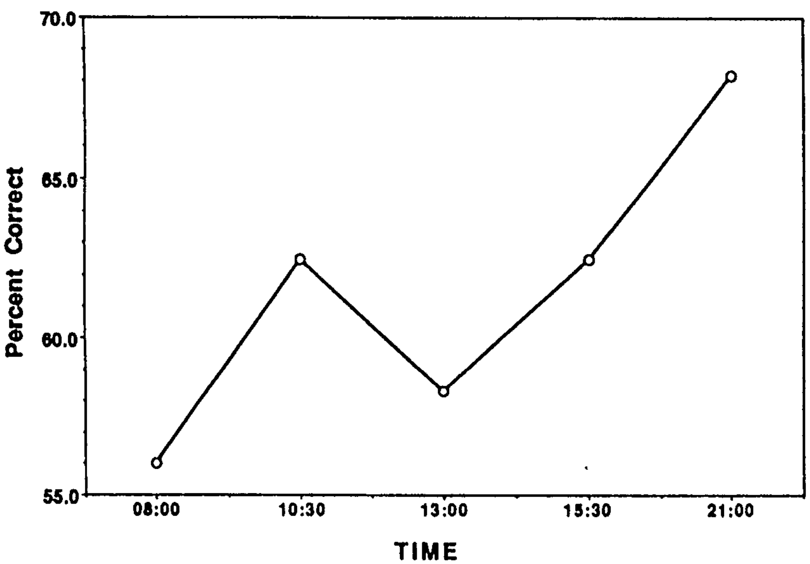


Figure 3. Vigilance (based on data from Blake, 1967)

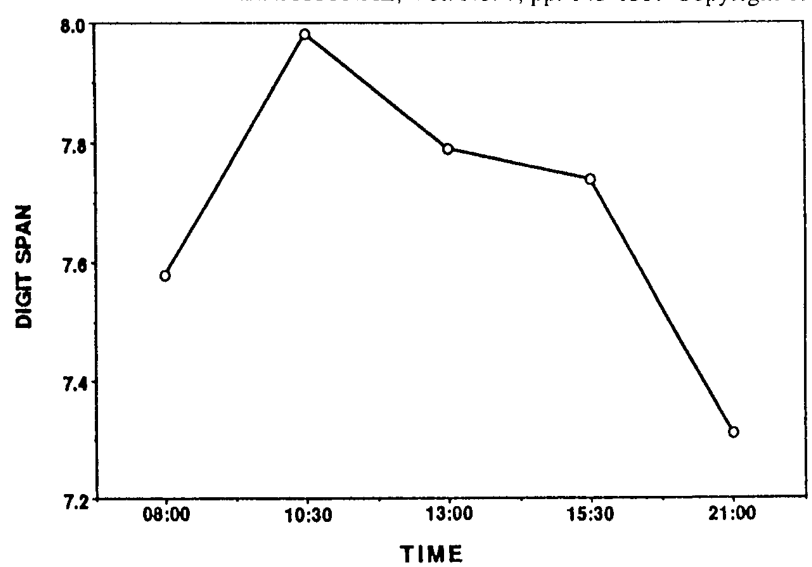


Figure 4. Digit Span (based on data from Blake, 1967)

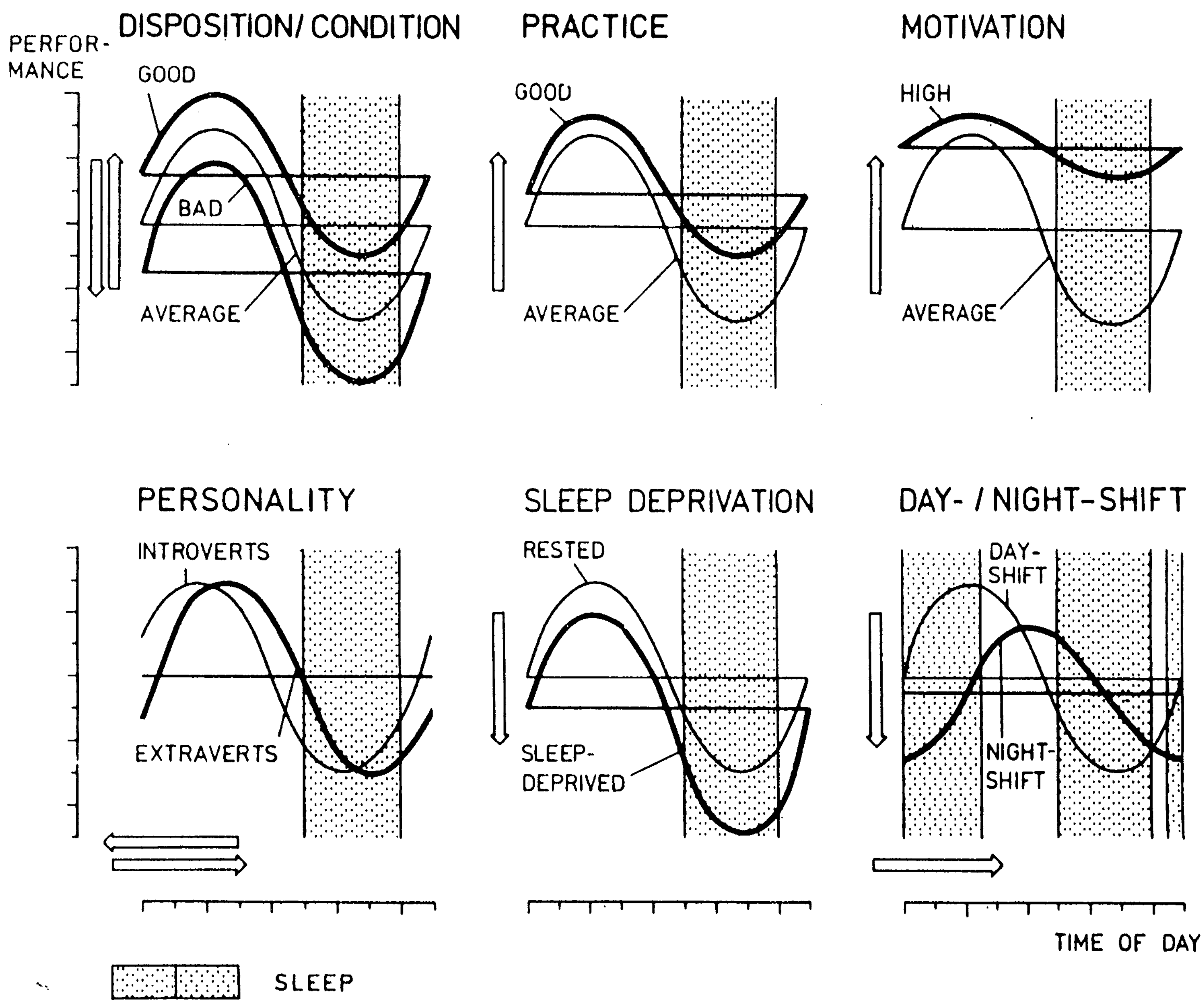


Figure 5. Factors Affecting Circadian Rhythms. Reprinted with permission of the Aerospace Medical Association from "Air operations and circadian performance rhythms," by Klein et al., AVIATION SPACE AND ENVIRONMENTAL MEDICINE,Vol. No. 47, pp. 221-230. Copyright 1976.

Folkard & Monk, 1979; Rutenfranz & Colquhoun, 1979), although not all authors agree on this point (Johnson et al., 1992; Maury & Quéinnec, 1993).

Effects of circadian rhythms can be difficult to separate from those of duration of wakefulness. Different cognitive functions appear to be more affected by one or the other of these factors. Folkard and Totterdell (1993) used a 30-hr work/rest cycle to separate the pereformance effects of circadian rhythms from those of time awake. They studied 3 subjects living on the 30-hr work/rest cycle for 15 days. They found that tasks varied as to how much they are affected by fatigue (cumulative time awake) and circadian rhythms. The proportion of variance in performance that was explained by the endogenous (25 hr) cycle as compared to the exogenous (30 hr) cycle differed considerably among performance measures. For example, the endogenous component accounted for more than 60% of the explained variance in mean reaction time (RT) and number of lapses on a Four-Choice Reaction Time task. For speed and accuracy on a Five-Choice Memory Search task, less than 30% of the explained variance was related to the endogenous component. Much of the exogenous component related to the period of sleep deprivation at the end of each extended day (20-hr wake periods). Thus, susceptibility of task performance to mild sleep deprivation contributed to this finding, and longer periods of sleep deprivation would increase this effect (i.e., different types of performance are more or less affected by sleep deprivation). Another extended day-length study (Monk et al., 1983) produced similar findings. In that study, a subject lived by a 25.8-hr sleep/wake cycle. Speed on a manual dexterity task was related largely to the endogenous circadian temperature rhythm (a 24.8-hr cycle length), while speed on a verbal reasoning task showed a small contribution tied to the circadian temperature rhythm, with the majority of the variation being related to the 25.8-hr day.

Errors

In many situations, some aspects of performance will be much more critical than others. Often it is acceptable for individuals to work more slowly, as long as accuracy is maintained at an acceptable level. However, errors or total absence of performance could be disastrous. Some studies of real-world performance suggest these aspects of performance are particularly prone to circadian variation. Errors by meter readers showed a clear circadian rhythm, with more than twice as many errors made in the early morning than the late morning or late afternoon (Mitler et al., 1988). Errors

also showed a clear early-afternoon ("postlunch") peak. Drivers most often admitted falling asleep in the early morning and early afternoon periods, with 58% of such episodes occurring between 2300 and 0500 and 25% between 1200 and 1500 (Rutenfranz & Colquhoun, 1979). Errors among engine drivers showed a similar pattern (Hildebrandt, Rohmert, & Rutenfranz, 1974), although interestingly, the afternoon peak actually was higher than the early morning peak in that study. The Three-Mile Island and Chernobyl disasters both occurred during the circadian low period, and the Challenger accident was attributed partially to sleep loss and shift work during the early morning hours (Mitler et al., 1988).

Ribak et al. (1983) analyzed all Air Force (aircraft) accidents that had been attributed to pilot error over a 12-year period. The pattern of accidents suggested that the closer a pilot was to his hour of awakening (presumed to be 0600), the more likely he was to make an accident-causing error. A late afternoon and early evening increase was thought possibly related to endogenous circadian rhythms. Since data from night flights do not appear to be included, it is possible that the increased accidents closer to the time of awakening relate to proximity to the circadian low period. Automobile accidents associated with a driver dozing off and single car accidents are known to occur more frequently during the late-night or early-morning hours (Harris, 1976). Similarly, in a survey of industrial workers, more than 50% admitted sometimes falling asleep on the night shift, much more than on any other shift (Coleman & Dement, 1986).

Whether rare but potentially disastrous events, such as falling asleep at the wheel, should be included in a model is a difficult question. If a model is to be used only to predict likely outcomes in various circumstances, such events probably can be discounted. However, if the model is to be used to help plan the best course of action, then such factors should be considered so steps can be taken to prevent them. For example, since individuals often seem to be unable to predict whether they are about to fall asleep (Itoi et al., 1993), incorporating measures into a mission plan to prevent personnel from falling asleep during critical periods is particularly important.

Circadian Rhythms and SUSOPS

Allowance for the effects of circadian rhythms is especially important in modeling of performance in sleep-deprived subjects because circadian rhythms interact with the effects of sleep

deprivation. If an individual has accumulated a significant sleep debt and is required to work at the low point of his or her circadian performance rhythm, alertness and performance will be particularly poor (Babkoff, Mikulincer, Caspy, & Carasso, 1989). Figure 6 re-plots placebo group speed and accuracy data from one task in a 64-hr sleep-deprivation study reported by Babkoff et al. (1992). A roughly sinusoidal performance rhythm across the 24-hr cycle can be seen overlaying an overall downward slope related to the effects of sleep deprivation. When possible, the final portion of a SUSOP should not coincide with the circadian low period (Wegmann & Klein, 1984).

The effects of circadian rhythms can be more pronounced than those of sleep deprivation. For example, in a study of circadian rhythm and fatigue effects in simulated long-duration flights, Perelli (1980) found that performance decrements due to flying at night were greater than those from cumulative fatigue related to work duration. Likewise, a study comparing conventional PAB tasks to a synthetic work task (SYNWORK) during SUSOPS found that the PAB tasks were more sensitive to sleep deprivation but SYNWORK, which is more like real-world performance, manifested a stronger circadian rhythm (Elsmore et al., 1995) .

Sleep deprivation and circadian rhythms are not simply additive. The effect of increased time awake is greatest around the time of minimum body temperature and least around its maximum. Because of this nonlinear relationship, performance degradations during a night of sleep deprivation may be worse than performance during the daytime the following day or two, despite increased duration of sleep deprivation. This can be seen in Figure 6, where performance the first night (WED, 0330) is worse than performance after more than 48 hr of sleep deprivation (THU, 0845 to 2045). Figure 7 shows a three-dimensional relationship (performance vs. duration of wakefulness vs. time of day) from a study by Dijk, Duffy, and Czeisler (1992) in which differing durations of wakefulness at different times of day were achieved by having subjects live by a 28-hr day (18 hr wake, 10 hr sleep). Eventually such a three-way function could be a valuable component of a model of cognitive performance. However, the Dijk et al. report is based on a preliminary study (only 2 subjects). Also, that study involved no real sleep deprivation. Effects of elapsed times awake significantly longer than the usual wake period may interact with circadian rhythms in a qualitatively different way than with shorter wake periods.

The differential effects of sleep deprivation at different circadian phases means that the

variations in performance become much greater relative to the mean as sleep deprivation progresses. Fröberg, Karlsson, Levi, and Lidberg (1975) studied circadian rhythms of shooting range performance and self-rated fatigue, along with physiological measures, in subjects who were tested at 3-hr intervals during 72 hr of sleep deprivation. Shooting performance showed a somewhat irregular circadian rhythm, with an average acrophase at around 1700 and a nadir around the time of peak fatigue (0500) (Figure 8). This pattern was clearest for number of shots. Number of hits and percentage of hits showed less apparent circadian rhythms. The mean daily performance decreased over the sleep-deprivation period, while the amplitude of circadian variation increased. On Day 1 of the study, when sleep deprivation was minimal, the mean number of shots made by the only group of subjects who completed the full 72-hr sleep-deprivation protocol was 1,239, and the amplitude of the circadian rhythm of shooting performance was 130. Thus, the peak-to-trough range was about 20% of the mean, possibly discountable within the range of accuracy that might be expected from a performance model. However, on the third day, mean performance was decreased by almost half and amplitude of the circadian rhythm had more than doubled. Therefore, the peak-to-trough range was almost 80% of the mean, which is large enough to be of concern to a performance model. Performance on the second day was intermediate, with a range equal to about 60% of the mean. These data show that if circadian rhythms are not taken into account in modeling performance during SUSOPS, performance estimates could be grossly off.

The increased amplitudes of circadian performance rhythms during sleep deprivation are not mediated by increased hormonal fluctuations. Indeed, the effects of sleep deprivation on amplitudes of hormonal circadian rhythms appear to be opposite of those on cognitive performance. Opstad (1994) reported a study of hormones and mental performance (Digit Symbol and Logical Reasoning tasks) in subjects undergoing almost total sleep deprivation during a strenuous 5-day training course. They found that the circadian variation of a number of hormones had been virtually abolished by the end of the course. In contrast, the amplitude of the performance rhythm increased from about $\pm$ 5% to $\pm$ 30% of the mean.

While individuals tend to have difficulty sleeping at some times of day, as compared with the night (Åkerstedt & Gillberg, 1981a, 1981b), once subjects are significantly sleep deprived getting to sleep generally is not a problem. Neither the benefits (Dinges, Orne, Whitehouse, & Orne, 1987) nor

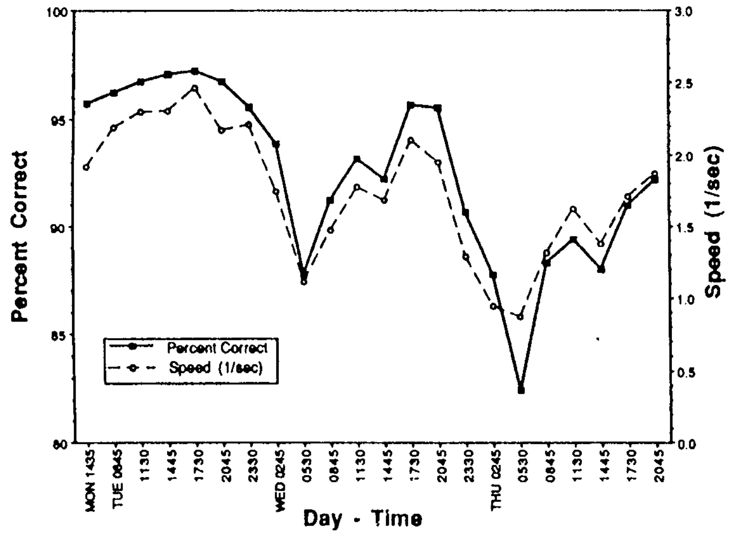


Figure 6. Four-Choice Reaction Time (Data from Babkoff, et al., 1992)

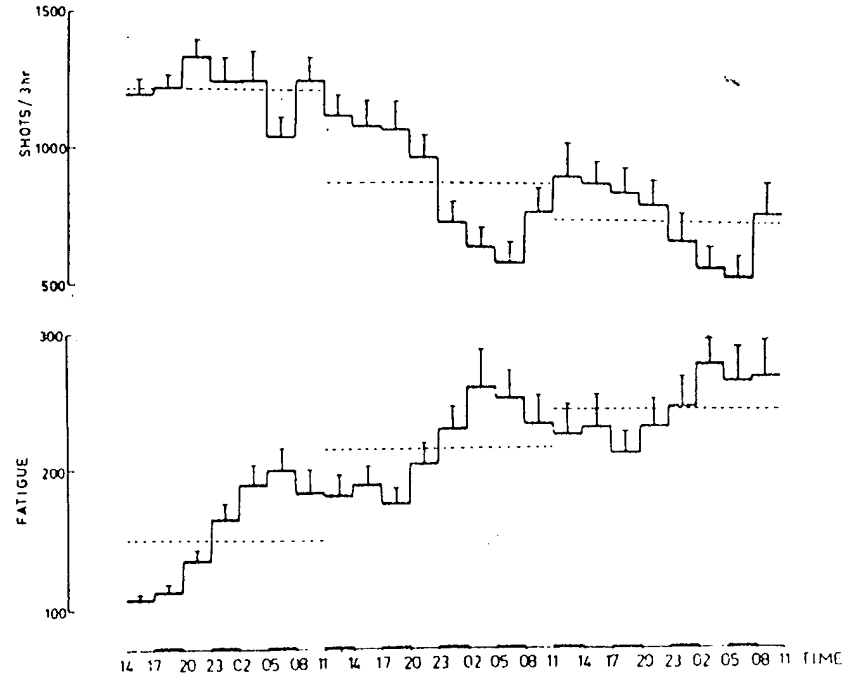


Figure 8. Shooting Performance and Fatigue During Sleep Deprivation. Reprinted by permission of Elsevier Science Inc. from "Circadian rhythms of catecholamine excretion, shooting range performance and self-ratings of fatigue during sleep deprivation," by Fröberg et al. BIOLOGICAL PSYCHIATRY, Vol. No. 2, pp. 185-188. Copyright 1975 by the Society of Biological Psychiatry.

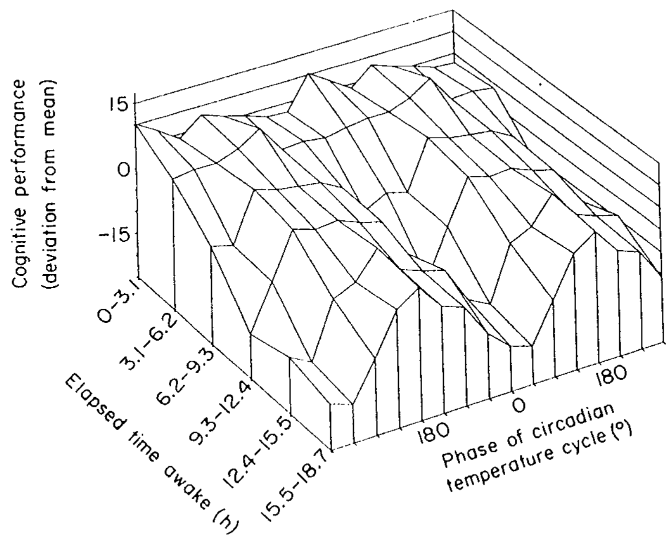


Figure 7. Performance vs. Time Awake and Circadian Phase. Reprinted with permission of JOURNAL OF SLEEP RESEARCH from "Circadian and sleep/wake dependent aspects of subjective alertness and cognitive performance.," by Dijk, et al., JOURNAL OF SLEEP RESEARCH, Vol. No. 1, pp. 112-117. Copyright 1992.

the detrimental sleep inertia effects of naps (Naitoh, Kelly, & Babkoff, 1993) show time of day differences. This simplifies including effects of naps in a model.

Jet Lag

If a model takes circadian rhythms into account, then it is absolutely necessary that it also take the effects of travel across time zones (jet lag) into account. Travel across time zones prior to military activity is not a rare event. If a model does not allow for this, circadian functions incorporated into a model could decrease rather than increase the accuracy of performance estimation. For example, immediately after crossing 12 time zones, the times of the peaks and valleys of performance will be 12 hr out of phase with local time. For night work, this can be an advantage. If personnel remain synchronized to home base time after crossing many time zones, they will show their best performance during the night shift (Neri & Shappell, 1994). How long it takes to adjust to new local time depends to a great extent on how much and when outdoor light exposure occurs, with the sleep-wake schedule and other time cues contributing to a lesser extent. With maintenance of the home-base sleep-wake schedule, avoidance of sunlight, and administration of melatonin prior to bedtime, synchronization to home-base time may be maintained indefinitely (Comperatore, Lieberman, Crowley, & Kirby, 1996).

Generally, phase advances (eastward travel) are adjusted to by phase advancing the internal rhythms, and phase delays (westward travel) by phase delaying. However, the fact that endogenous cycle lengths are longer than 24 hr makes it more difficult to advance than to delay human circadian rhythms. Therefore, some individuals adjust to large phase advances by delaying rather than advancing rhythms. After eastward travel of more than 9 time zones, the majority of individuals may adjust by phase delaying their rhythms (e.g., Gundel & Wegmann, 1989). Different types of performance may resynchronize at different rates (Monk, Knauth, Folkard, & Rutenfranz, 1978). When activity and light exposure patterns conform to the diurnal period of local time, adjustment is reported to occur at the rate of about 90 min per day after westward travel and 60 min per day after eastward travel (Aschoff, 1978). Appropriately timed artificial bright light can facilitate large shifts in a relatively short period of time (Czeisler et al., 1986; Czeisler et al., 1989; Minors, Waterhouse, & Wirz-Justice, 1991). Natural light can have similar effects. Subjects allowed outside in a new time

zone resynchronized about 50% faster than did subjects confined to a hotel, even though both followed a normal sleep-wake schedule (Klein & Wegmann, 1980).

Light is not the only thing that may affect adjustment of circadian rhythms. Preliminary evidence indicates that exercise may promote phase delays, which may imply it will inhibit phase advances (Van Cauter, et al., 1993). Thus, the adjustment rate after multiple time zone crossings could depend upon individual activity level. Clearly, transport across time zones greatly complicates the amount of information that a model will need to be able to accurately predict circadian aspects of performance.

Individual Differences

Individual differences are relevant to modeling performance in defining the variability of circadian effects. Age is fairly well documented as having a negative effect on an individual's ability to perform shift work, particularly night work (Härmä, Hakola, & Laitinen, 1993) and susceptibility to jet lag (Gander, De Nguyen, Rosekind, & Connell, 1993). Also, middle-aged personnel may be more susceptible than young people to decrements related to the lesser circadian low period in the afternoon (Summala & Mikkola, 1994). To the extent that critical members of a mission requiring night work or SUSOPS may be older (e.g., the leader), a performance model might need to take this into account. However, the fact that older personnel are likely to be better trained and that better trained or more skilled individuals tend to show less variation across the 24-hr cycle and less decrement at night might counterbalance this in many cases (Klein et a., 1976).

Morningness/eveningness ("larks" vs. "owls") is a characteristic that has been investigated in relation to its effects on performance circadian rhythms and ability to perform night work. Some performance tasks show very similar performance rhythms between morning and evening types. Others show very different patterns in the two types (Kerkoff, 1985). Tasks involving a significant working memory component may differ more between the types. Monk and Leng (1986) found that speed of performance on a Single Letter Search Task had a similar rhythm peaking around 1600 in both types, but for speed of performance on a Logical Reasoning task the acrophases were 6 hr apart

(morning types: 0651, evening types: 1304).[3] Unfortunately, this study did not include nighttime testing, so it is uncertain whether the performance nadirs (probably of greater importance for modeling than the acrophase) are so disparate.

Whether an individual is a long or a short sleeper may be quite relevant to SUSOPS performance. Evidence indicates that individuals have inherently different sleep needs. Those with the greatest sleep requirement will show the greatest sleep-deprivation effects, and those with the least requirement will show the least effects (Foret, Benoit, & Merle, 1981). However, simply asking individuals how much they sleep may be insufficient to determine sleep need. For example, someone who is sleeping 5 hr a night but who is constantly tired is not a short sleeper, but rather a normal sleeper who is chronically sleep deprived. Chronic sleep deprivation is so prevalent in modern society that the "National Sleep Debt" is proposed to be a major problem (Dement, 1994).

Models

Monk (1982) presented a method for modeling a performance rhythm that might be able to compensate for the variable phase position of the circadian rhythms of different cognitive functions. His model derives an alertness rhythm from the best-fitting sinusoid to a subject's body temperature data (using a peak at 1800 provided good fit and accounted for > 80% of variability in his subjects). This is combined with an inverted U function representing the relationship of alertness and performance for a given type of behavior. For example, in low memory load tasks very high alertness might be optimal, and the performance rhythm would be close to the temperature rhythm. In high memory load tasks, on the other hand, lower alertness might be preferable, and the combined functions would produce a performance rhythm that decreased during the day, as shown in Figure 9. A limiting factor to this technique is that the exact alertness performance relationship has not been clearly established, even for most simple types of performance, let alone for the complex behaviors personnel may be required to perform in military operations.

Åkerstedt and Folkard (1995) devised a computerized model of alertness that combines the

---

[3]It should be noted that both these acrophases differ considerably from those reported by Gillooly et al. (1990). This study used a 10-min paper and pencil test, while the Gillooly study used a computerized task for which the duration was not specified. Such different findings for similar cognitive tests make modeling more difficult. However, it is the low point rather than the peak that is most critical, and reported trough times have been fairly consistent.

effects of circadian rhythms (process C) with those related to duration of wakefulness and/or sleep (process S). This is diagramed in Figure 10. The input to this model is the times of rising and going to bed during the time period of interest. The formulas for the homeostatic component during waking (S), the homeostatic component during sleep (S'), and the circadian component (C) in this model are as follows:

$S = (Sa - L)e \wedge - 0.0343t + L$

(where Sa = value of S at awakening, L = Lower asymptote, and t = time since awakening)

$S' = U - (U - Sr)e \wedge -0.381t$

(where Sr = value of S at retiring, U = upper asymptote, and t = time since falling asleep)

$C = M \cos(t - p)\pi / 12$

(where M = amplitude, p = acrophase in decimal hours, and t = time of day in decimal hours)

This model successfully predicts both subjective and EEG-based sleepiness measures in situations of irregular sleep and waking. It is also reported to predict performance.

Mitler (1991) proposed the following formulas to predict performance and sleep tendency:

$P = 1 / K [K - \cos^2 (t + phi)) (1 - \cos (t + \mathrm{phi}) / SD)2]$

Sleep tendency = 1 - P

Where P = performance, K = scaler, t = clock time, *phi* = physiological phase offset, and SD = sleep-deprivation factor. The sleep tendency formula shows a highly statistically significant agreement with automobile accident and human mortality data.

Gander, Kronauer, & Graeber (1985) reported on a model simulating the effects of two coupled circadian pacemakers to predict resynchronization during jet lag. The X oscillator represents the major determinant of phase of the circadian rhythm of core temperature. The Y oscillator regulates the sleep-wake cycle, with sleep tending to begin 120° before Y rises through the mean and to end as Y crosses the mean (for a one third sleep fraction). This model is shown in Figure 11. The model predicts rate of adjustment depending on the rhythm being measured, the number of time zones crossed, the flight direction, and the strength of available time cues. This model is more complicated, but it is probably also more accurate than the "60 minutes per day after eastward travel, 90 minutes per day after westward travel" rule of thumb.

Samn and Perelli (1982) published an algorithm for estimating aircrew fatigue in computer-

simulated airlift operations. Factors taken into account include previous sleep amount, shifting of the sleep period, crossing of time zones, number of consecutive duty days, and number of prior duty days exceeding 16 hr. Some components of the algorithm are shown to correlate with subjective fatigue scores. However, it is unclear whether the overall algorithm has been validated. This model is too long and complex to discuss here. The reader is referred to the original publication.

Conclusions and Recommendations

This report documents that the magnitude of the circadian variation in cognitive performance sometimes is large enough to require inclusion in models of cognitive performance. Otherwise, performance will not be accurately estimated. This is particularly true for models of performance during SUSOPS or other situations in which sleep is markedly decreased. Additionally, any model that includes circadian rhythms must make allowance for readjustments after travel across multiple time zones. Otherwise, inclusion of circadian factors could decrease rather than increase accuracy of a model.

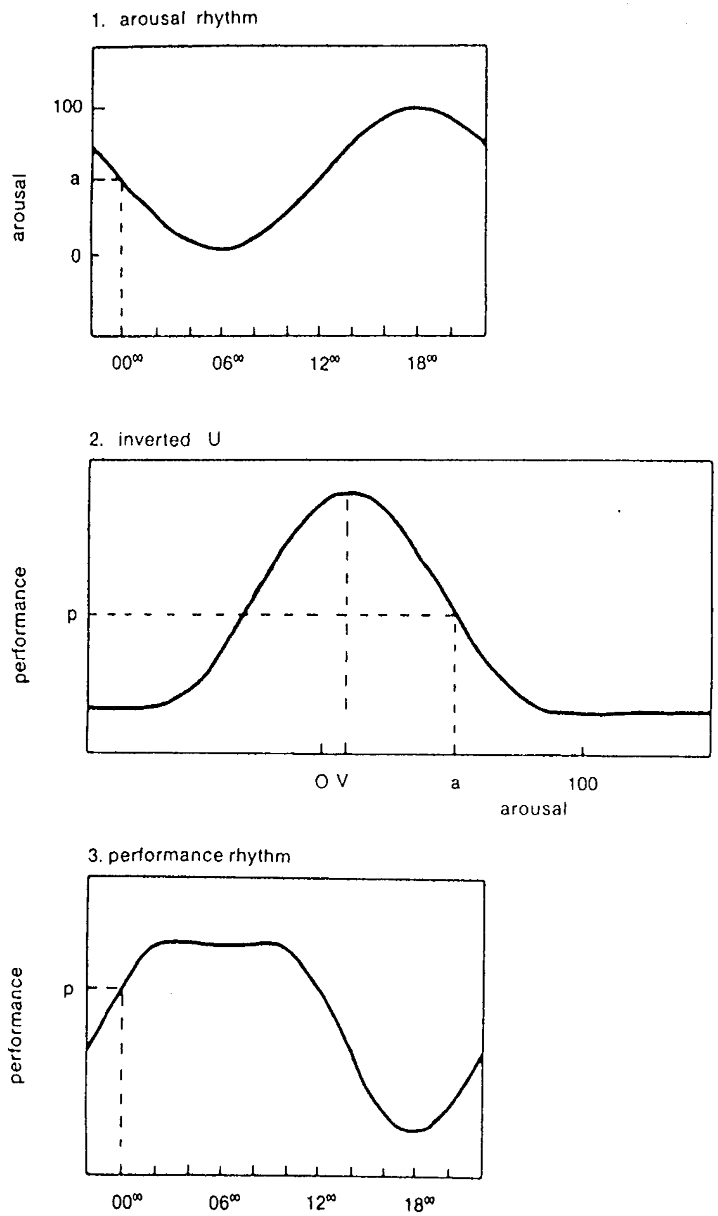


Figure 9. Arousal Theory Model. Reprinted with permission of CHRONOBIOLOGIA from "The arousal model of time of day effects in human performance efficiency," by Monk, CHRONOBIOLOGIA, Vol. No. 9, pp. 49-54. Copyright 1982.

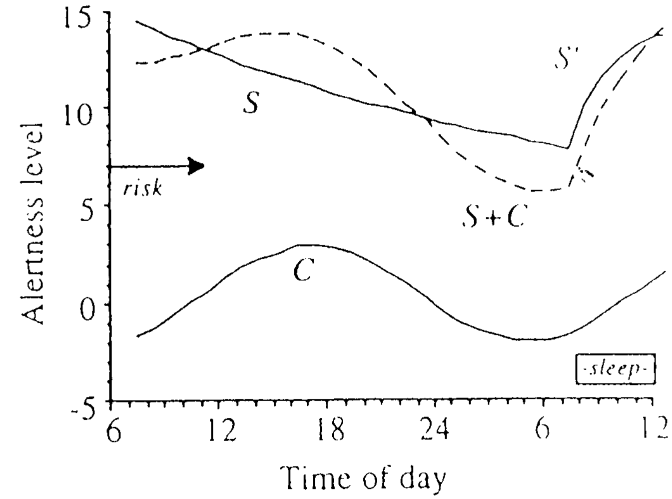
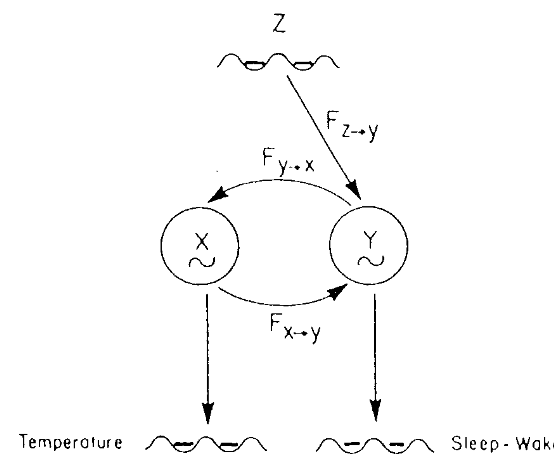


Figure 10. Process C - Process S Model. Reprinted with permission of SLEEP from "Validation of the S and C components of the three-process model of alertness regulation," by Åkerstedt & Folkard, SLEEP, Vol. No. 18, pp. 1-6. Copyright 1995.



Oscillator X $\left[\ddot{X} + \mu_x(-1 + X^2)\dot{X} + \omega_x^2 X\right] + F_{y \to x}\dot{Y} = 0$

Oscillator Y $\left[\ddot{Y} + \mu_y(-1 + Y^2)\dot{Y} + \omega_y^2 Y\right] + F_{x \to y}\dot{X} = \begin{cases} 0 \\ F_{Z \to y} Z \end{cases}$

Figure 11. Jet Lag Resynchronization Model. Reprinted with permission of the American Physiological Society from "Phase shifting two coupled circadian pacemakers: implications for jet lag. AMERICAN JOURNAL OF PHYSIOLOGY, Vol. No. 249, pp. R704-R719.

REFERENCES

Åkerstedt, T., & Folkard, S. (1995). Validation of the S and C components of the three-process model of alertness regulation. *Sleep, 18*, 1-6.

Åkerstedt, T., & Gillberg, M. (1981a). The circadian pattern of unrestricted sleep and its relation to body temperature. In L. C. Johnson, D. I. Tepas, W. P. Colquhoun, & M. J. Colligan (Eds.), *The twenty-four hour workday: proceedings of a symposium on variations in work-sleep schedules* (pp.. 605-624) [DHHS(NIOSH) Publication No. 81-27]. Cincinnati, OH: Public Health Service, Centers for Disease Control, National Institute for Occupational Safety and Health, Division of Biomedical and Behavioral Sciences.

Åkerstedt, T., & Gillberg, M. (1981b). The circadian variation of experimentally displaced sleep. *Sleep, 492,* 159-169.

Aschoff, J. (1978). Problems of re-entrainment of circadian rhythms: asymmetry effect, dissociation and partition. In I. Assenmacher, & D. S. Farner (Eds.), *Environmental endocrinology* (pp. 185-194). Berlin, Germany: Springer-Verlag.

Babkoff, H., Kelly, T. L., Matteson, L. T., Gomez, S. A., Lopez, A., Hauser, S., Naitoh, P., & Assmus, J. (1992). Pemoline and methylphenidate: interaction with mood, sleepiness, and cognitive performance during 64 hours of sleep deprivation. *Military Psychology, 4,* 235-265.

Babkoff, H., Mikulincer, M., Caspy, T., & Carasso, R. L. (1989). The implications of sleep loss for circadian performance accuracy. Work & Stress, 3, 3-14.

Blake, M. J. F. (1967). Time of day effects on performance in a range of tasks. *Psychonomic Science, 9,* 349-350.

Brown, F. M., & Graeber, R. C. (Eds.). (1982). *Rhythmic aspects of behavior.* Hillsdale, NJ: Lawrence Erlbaum Associates.

Coleman, R. M., & Dement, W. C. (1986). Falling asleep at work: a problem for continuous operations (Abstract). *Sleep Research, 15,* 265.

Comperatore, C. A., Lieberman, H. L., Crowley, J. S., & Kirby, A. W. (1996). Melatonin maintains alertness and prevents sleep loss during an army aviation mission involving rapid deployment and night operations. *Aviation Space and Environmental Medicine*, in press.

Cugini, P., De Palma, L., Di Simone, S., Piernatale, L., Battisti, P., Coppola, A., & Leone, G. (1993). Circadian rhythm of cardiac output, peripheral vascular resistance, and related variables by beat-to-beat monitoring. *Chronobiology International, 10,* 73-78.

Czeisler, C. A., Allan, J. S., Strogatz, S. H., Ronda, J. M., Sánchez, R., Ríos, C. D., Freitag, W. O., Richardson, G. S., & Kronauer, R. E. (1986). Bright light resets the human circadian pacemaker independent of the timing of the sleep-wake cycle. *Science, 223,* 667-671.

Czeisler, C. A., Kronauer, R. E., Allan, J. S., Duffy, J. F., Jewett, M. E., Brown, E. N., & Ronda, J. M. (1989). Bright light induction of strong (type 0) resetting of the human circadian pacemaker. *Science, 244,* 1328-1333.

Dement, W. C. (1994, February). *Sleep: A private or public issue?* Presentation at conference on Sleep and the Public Safety, Scripps Clinic and Research Foundation, San Diego, CA.

Dijk, D. J., Duffy, J. F., & Czeisler, C. A. (1992). Circadian and sleep/wake dependent aspects of subjective alertness and cognitive performance. *Journal of Sleep Research, 1,* 112-117.

Dinges, D. F., Orne, M. T., Whitehouse, W. G., & Orne, E. C. (1987). Temporal placement of a nap for alertness: contributions of circadian phase and prior wakefulness. *Sleep, 10,* 313-329.

Elsmore, T. F., Hegge, F. W., Naitoh, P., Kelly, T., Schlangen, K., & Gomez, S. (1995). *A comparison of the effects of sleep deprivation on synthetic work performance and a conventional performance assessment battery* (NHRC Tech. Rep. No. 95-6). San Diego, CA: Naval Health Research Center.

Folkard, S. (1981). Shiftwork and performance. In, L. C. Johnson, D. I. Tepas, W. P. Colquhoun, & M. J. Colligan (Eds.), *The twenty-four hour workday: proceedings of a symposium on variations in work-sleep schedules* (pp. 347-373) [DHHS(NIOSH) Publication No. 81-27]. Cincinnati, Ohio: Public Health Service, Centers for Disease Control, National Institute for Occupational Safety and Health, Division of Biomedical and Behavioral Sciences.

Folkard S., Knauth, P., Monk, T. H., & Rutenfranz, J. (1976). The effect of memory load on the circadian variation in performance efficiency under a rapidly rotating shift system. *Ergonomics, 19,* 479-488.

Folkard, S., & Monk, T. H. (1979). Shiftwork and performance. *Human Factors, 21,* 483-492.

Folkard, S., & Totterdell, P. (1993). Dissecting circadian performance rhythms: implications for shift work. *Ergonomics, 36,* 183-288.

Folkard, S., Wever, R. A., & Wildgruber, C., M. (1983). Multi-oscilatory control of circadian rhythms of human performance. *Nature, 305,* 223-226.

Foret, J., Benoit, O., & Merle, B. (1981). Circadian "profile" of short and long sleepers. In, L. C. Johnson, D. I. Tepas, W. P. Colquhoun, & M. J. Colligan (Eds.), *The twenty-four hour workday: proceedings of a symposium on variations in work-sleep schedules* (pp. 625-639) [DHHS(NIOSH)

Publication No. 81-27]. Cincinnati, OH: Public Health Service, Centers for Disease Control, National Institute for Occupational Safety and Health, Division of Biomedical and Behavioral Sciences.

Fröberg, J. E., Karlsson, C. G., Levi, L., & Lidberg, L. (1975). Circadian rhythms of catecholamine excretion, shooting range performance and self-ratings of fatigue during sleep deprivation. *Biological Psychology, 2,* 175-188.

Gander, P. H., De Nguyen, B. E., Rosekind, M. R., & Connell, L. J. (1993). Age, circadian rhythms, and sleep loss in flight crews. *Aviation, Space & Environmental Medicine, 64,* 189-195.

Gander, P. H., Kronauer, R. E., & Graeber, R. C. (1985). Phase shifting two coupled circadian pacemakers: implications for jet lag. *American Journal of Physiology, 249 (Regulatory Integrative Comp. Physiol. 18),* R704-R719.

Gillooly, P. B., Smolensky, M. H., Albright, D. L., Hsi, B., & Thorne, D. R. (1990). Circadian variation in human performance evaluated by the Walter Reed performance assessment battery. *Chronobiology International, 7,* 143-153.

Gundel, A., & Wegmann, H. M. (1989). Transition between advance and delay responses to eastbound transmeridian flights. *Chronobiology International, 6,* 147-156.

Härmä, M., Hakola, T., & Laitinen, J. T. (1993). The relation of age to adaptation to night work. *Ergonomics, 36,* 315.

Harris, W. (1976). Fatigue, circadian rhythm, and truck accidents. In R. Mackie (Ed.), *Vigilance: theory, operational performance, and physiological correlates* (pp. 133-146). New York: Plenum Press.

Hildebrandt, G., Rohmert, W., & Rutenfranz, J. (1974). 12 and 24 hour rhythms in error frequency of locomotive drivers and the influence of tiredness. *International Journal of Chronobiology, 2,* 175-180.

Itoi, A., Cilveti, R., Voth, M., Dantz, B., Hyde, P., Gupta, A., & Dement, W. C. (1993). *Can drivers avoid falling asleep at the wheel? Relationship between awareness of sleepiness and ability to predict sleep onset.* Washington, DC: AAA Foundation for Traffic Safety.

Johnson, M. P., Duffy, J. F., Dijk, D. J., Ronda, J. M., Dyal, C. M., & Czeisler, C. A. (1992). Short-term memory, alertness and performance: a reappraisal of their relationship to body temperature. *Journal of Sleep Research, 1,* 24-29.

Kelly, T. L., Smith, D., & Naitoh, P. (1989). *Melatonin, light and circadian cycles* (NHRC Tech. Rep. No. 89-38). San Diego, CA: Naval Health Research Center.

Kerkoff, G. A. (1985). Inter-individual differences in the human circadian system: a review. *Biological Psychology, 20,* 83-112.

Klein, K. E., & Wegmann, H. M. (1979). Circadian rhythms of human performance and resistance: operational aspects. In *Sleep, wakefulness and circadian rhythm* (pp. 2-1 to 2-17) [AGARD Lecture Series No. 105]. Neuilly sur seine, France: North Atlantic Treaty Organization Advisory Group for Aerospace Research & Development.

Klein, K. E., & Wegmann, H. M. (1980). *Significance of circadian rhythms in aerospace operations* (AGARDograph No. 247). Neuilly sur Seine, France: Advisory Group for Aerospace Research & Development.

Klein, K. E., Wegmann, H. M., Athanassenas, G., Hohlweck, H., & Kuklinski, P. (1976). Air operations and circadian performance rhythms. *Aviation Space and Environmental Medicine, 47,* 221-230.

Maury, P., & Quéinnec, Y. (1993). Qualitative changes in recall memory during day and night shifts. *Ergonomics, 36,* 289-297.

Minors, D. S., Waterhouse, J. M., & Wirz-Justice, A. (1991). A human phase-response curve to light. *Neuroscience Letters, 133,* 36-40.

Mitler, M. M. (1991). Two-peak 24-hour patterns in sleep, mortality, and error. In J. H. Peter, T. Penzel, T. V. Podsxus, & P. Wichert (Eds.), *Sleep and Health Risk* (pp. 65-67). Berlin, Germany: Springer-Verlag.

Mitler, M. M., Carskadon, M. A., Czeisler, C. A., Dement, W. C., Dinges, D. F., & Graeber, R. C. (1988). Catastrophes, sleep, and public policy: consensus report. *Sleep, 11,* 100-109.

Monk, T. H. (1982). The arousal model of time of day effects in human performance efficiency. *Chronobiologia, 9,* 49-54.

Monk, T. H., Knauth, P., Folkard, S., & Rutenfranz, J. (1978). Memory-based performance measures in studies of shiftwork. *Ergonomics, 21,* 819-826.

Monk, T. H., & Leng, V. C. (1986). Interactions between inter-individual and inter-task differences in the diurnal variation of human performance. *Chronobiology International, 3,* 171-177.

Monk, T. H., Weitzman, E. D., Fookson, J. E., Moline, M. L., Kronauer, R. E., & Gander, P. H. (1983). Task variables determine which biological clock controls circadian rhythms in human performance [Letter]. *Nature, 304,* 543-545.

Naitoh, P., Kelly, T., & Babkoff, H. (1993). Sleep inertia: best time not to wake up? *Chronobiology*

International, 10, 109-118.

Neri, D. F., & Shappell, S. A. (1994). The effect of combat on the work/rest schedules and fatigue of naval aviators during Operations Desert Shield and Desert Storm. *Military Psychology, 6,* 141-162.

Nicolau, G. Y., & Haus, E. (1989). Chronobiology of the endocrine system. *Endocrinologie, 27,* 153-183.

Opstad, P. K. (1994). Circadian rhythm of hormones is extinguished during prolonged physical stress, sleep and energy deficiency in young men. *European Journal of Endocrinology, 131,* 56-66.

Perelli, L. P. (1980). *Fatigue stressors in simulated long-duration flight: effects on performance, information processing, subjective fatigue, and physiological cost* (Report No. SAM-TR-80-49). Bracks Air Force Base, TX: US Air Force School of Aerospace Medicine.

Ribak, J., Ashkenazi, I. E., Klepfish, A., Avgar, D., Tall, J., Kallner, B., & Noyman, Y. (1983). Diurnal rhythmicity and air force flight accidents due to pilot error. *Aviation, Space, and Environmental Medicine, 54,* 1096-1099.

Rivera-Coll, A., Fuentes-Arderiu, X., & Diez-Noguera, A. (1993). Circadian rhythms of serum concentrations of 12 enzymes of clinical interest. *Chronobiology International, 10,* 190-200.

Rutenfranz, J., & Colquhoun, W. P. (1979). Circadian rhythms in human performance. *Scandinavian Journal of Work Environment and Health, 5,* 167-177.

Samn, S. W., & Perelli, L. P. (1982). *Estimating aircrew fatigue: a technique with application to airlift operations* (Report SAM-TR 82-21). Brooks Air Force Base, TX: US Air Force School of Aerospace Medicine.

Sletvold, O., Smaaland, R., & Laerum, O. D. (1991). Cytometry and time-dependent variations in peripheral blood and bone marrow cells: a literature review and relevance to the chronotherapy of cancer. *Chronobiology International, 8,* 235-280.

Summala, H., & Mikkola, T. (1994). Fatal accidents among car and truck drivers: effects of fatigue, age, and alchol consumption. *Human Factors, 36,* 312-326.

Van Cauter, E., Sturis, J., Byrne, M. M., Blackman, J. D., Scherberg, N. H., Leproult, R., Refetoff, S., & Van Reeth, O. (1993). Preliminary studies on the immediate phase-shifting effects of light and exercise on the human circadian clock. *Journal of Biological Rhythms, 8 (Suppl.),* 99-108.

Wegmann, H. M., & Klein, K. E. (1984). *Circadian rhythms and sustained operations* (AGARD Conference Procedings, No. 338). Neuilly sur Seine, France: North Atlantic Treaty Organization, Advisory Group for Aerospace Research and Development.

Wilkinson, R. T. (1982). The relationship between body temperature and performance across circadian phase shifts. In, F. M. Brown & R. C. Graeber (Eds.), *Rhythmic Aspects of Behavior.* Hillsdale, NJ: Lawrence Erlbaum Associates.

Winget, C. M., DeRoshia, C. W., & Holley, D. C. (1985). Circadian rhythms and athletic performance. *Medicine and Science in Sports and Exercise, 17,* 498-516.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY ***(Leave blank)***

2. REPORT DATE
5 February 1996

3. REPORT TYPE & DATE COVERED
Interim., 1 Oct 94- 1 Sep 95

4. TITLE AND SUBTITLE Circadian Rhythms: Importance for Models of Cognitive Performance

5. FUNDING NUMBERS
Program Element: 61153N
Work Unit Number:
MR04101.003-6410

6. AUTHOR(S) Tamsin Lisa Kelly

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Naval Health Research Center
P.O. Box 85122
San Diego, CA 92186-5122

8. PERFORMING ORGANIZATION
Report No. 96-1

9. SPONSORING/MONITORING AGENCY NAMES(S) AND ADDRESS(ES)
Naval Medical Research and Development Command
National Naval Medical Center
Building 1, Tower 2
Bethesda, MD 20889-5044

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES This report was prepared as input for Work Unit No. 63706N.M0096.002.6417

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT ***(Maximum 200 words)*** Literature concerning circadian rhythms was reviewed. This literature shows that the effects of circadian rhythms on cognitive performance are large enough to have practical significance for models of cognitive performance. Expressed as a percentage of mean performance, circadian variation averages about 20% in laboratory studies and 40% in field studies. Decrements due to circadian rhythms can be greater than those due to sleep deprivation. Sleep deprivation amplifies performance rhythms, causing greater decrements at the time of the circadian nadir (early morning) than during the daytime. Thus, decrements in the early morning can be quite dramatic in sleep-deprived subjects. Most cognitive performance rhythms are fairly well aligned with the circadian rhythm of body temperature. Tasks involving a high short-term memory load may be an exception, sometimes showing rhythms almost 180° out of phase with temperature. After travel across multiple time zones, individuals intitially show rhythms in phase with the home base clock. Rhythms adjust to the new time zone at a rate of about 90 min per day after westward travel and 60 min per day after eastward travel. Several factors can speed or slow adjustment, particularly the timing and duration of bright light exposure. Any model that includes circadian rhythms must make allowance for readjustments after travel across multiple time zones. Otherwise, inclusion of circadian factors could decrease rather than increase accuracy of a model.

14. SUBJECT TERMS
circadian rhythms, cognitive performance, modeling, SUSOPS, sleep deprivation, jet lag

15. NUMBER OF PAGES
26

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	Unlimited